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ADP011123

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Nonlinearities and PIO with Advanced Aircraft Control Systems

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ABSTRACT

Design methods for advanced aircraft control systems include feedbacks to stabilize relaxed-static-stability vehicles, command and feedback shaping, and gain scheduling. Extensive use of such designs increases the risk of adverse nonlinear response to pilot control inputs. A common form of this adverse response is pilot-induced oscillation (PIO). This paper examines the relationship between nonlinearities in advanced aircraft control systems and PIO. The results of recent research clearly demonstrate that actuator rate limiting, alone, does not always cause PIO. Other factors, such as the degree of instability of the unaugmented airplane and level of excess demand on the control surface, are greater determinants of PIO susceptibility. The paper evaluates two other, less thoroughly documented, contributors to PIO – command shaping (sensitivity) and hysteresis in the flight controls. Inferences about their impact on PIO may be made, but there is not enough data to draw specific conclusions.

INTRODUCTION

In the past, it has been assumed that the typical sources of nonlinear response to linear cockpit commands are negligible, at least as far as their overall impact on flying qualities. With minimal augmentation this may be a reasonable assumption, since even the most extreme of such nonlinearities should normally have a much smaller impact on effective-vehicle dynamics than, say, uncertainties in control power. (Some forms of nonlinearity may even be considered favorable, such as controller breakout forces and command shaping.) There are no real design criteria in the published literature to aid the flight control system designer in dealing with such nonlinearities.

Most flight research programs conducted by the agencies and contractors in the United States over the past 50 years or so have made great attempts to minimize the presence of nonlinear response elements. This has been sensible when, for example, we want to study the impact of short-period damping and natural frequency on handling qualities. We simply would not want to allow some nonlinear element to dominate the results of such a study.

The use of modern aircraft design methods, such as relaxed static stability, multiply-redundant control surfaces, and thrust vectoring, provides the flight control system (FCS) designer with immense capability for tailoring the response of the airplane to meet every possible challenge. Such advanced flight control systems come with a price, however, and one

price seems to be the increased risk of pilot-induced oscillations (PIO) resulting from the unexpected interactions of the elements of the airframe and its FCS. Further, there is ample evidence that the major player in the occurrence of PIO in highly-augmented aircraft is the introduction of nonlinearities in the aircraft's response.¹

Concern about nonlinearities and their impact on flying qualities in general is certainly not new. The US military flying qualities specification MIL-F-8785C,² released in 1980, referred to an "equivalent" airplane that includes, for example, "flight control system nonlinearities and higher-order characteristics or aerodynamic nonlinearities" to which the requirements must apply. It is sometimes forgotten that the military flying qualities requirements are intended to be applied to such an equivalent airplane, thus accounting for known nonlinearities.

There are, unfortunately, several shortcomings with the US military flying qualities specifications. First, little research has been done to verify that significant nonlinearities affect flying qualities and PIO in a manner similar to equivalent changes in linear characteristics. Second, the specifications do not contain explicit requirements for the prevention of PIO, and while meeting the criteria certainly will reduce the risk of PIO, there are times that degraded flying qualities may be tolerable, but not PIO. Third, the extreme levels of nonlinearity that have been encountered in recent PIOs are generally not even considered to be possible during initial design and verification.

Several recent analytical, ground simulation, and flight research projects have investigated the impact of certain nonlinearities on both the identification of the aircraft from familiar frequency-response techniques, and the occurrence of PIO.^{3,4,5,6,7,8}

SOURCES OF NONLINEARITY

Some possible sources of nonlinearity are sketched in the representative flight control system block diagram in Figure 1. The most significant of these, in terms of PIO, are the rate limits that occur naturally on control actuators and those that are intentionally designed into the control system, in the form of command or software rate limits. These forms of limiting have received the most attention in recent years, and they will be the primary focus of this paper. Nonlinear elements in the cockpit effector, breakout and hysteresis, may contribute to PIO, and will be discussed. The final form of nonlinearity to be covered, command shaping, will be mentioned as well.

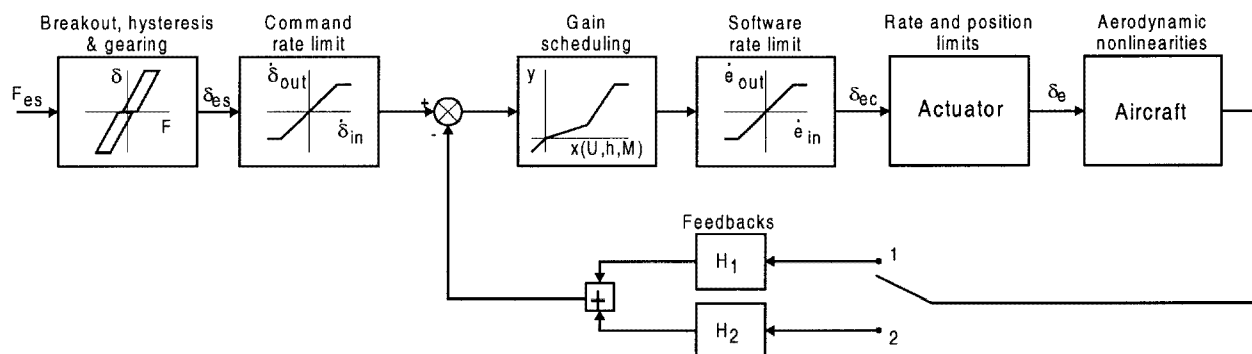


Figure 1. Some Sources of Nonlinearity in Modern Flight Control Systems

The effects of gain scheduling, mode switching, and aerodynamic nonlinearities on PIO have been reported but are not well-documented, and will not be discussed here.

All of the nonlinear elements described above can be represented for analytical purposes by simple describing functions.^{9,10} Still, their interactions with the effective aircraft dynamics can be complex, requiring more sophisticated methods to measure their impact.

RATE LIMITING

As Figure 1 indicates, there are many possible sources of rate limiting in the typical modern flight control system. Rate limiters in the pilot's command path (command rate limit), or located just before the surface command (software rate limit) are inserted intentionally. Rate limiting of the surface actuators occurs as a consequence of actuator design.

The occurrence of rate limiting with hydraulic actuators is quite common, since it is difficult for most actuators to provide both the rates and amplitudes of deflection demanded of them for more than very small commands. Such limiting is typically momentary and is not usually noticed in normal flight. It is only when the demand becomes significantly greater than the maximum rate achievable, for an extended period of time, that actuator rate limiting becomes an issue.

In truth, many recent PIOs experienced on highly-augmented aircraft involve not the rate-limiting of the aerodynamic surface actuators themselves, but rather software rate limiters. Several PIOs experienced during full-scale development of the C-17A, for example, were attributed to a software rate limiter, installed to protect against excessive aerodynamic loads from the pitching surfaces.¹¹ One of the steps taken to alleviate the C-17A's PIOs was relocation of the limiter to the pilot's command path.

In most cases, as long as the limiting is within the command loop structure as sketched in Figure 1, the observed response of the airplane is the same whether it is the actuator or software that rate-limits. In the case of the actuator, there will be a reduction in bandwidth that does not occur in the infinite-bandwidth software limiter. For all practical purposes, however, the differences between these types of limiter are insignificant. The effect on the airplane will be a loss of all augmentation, resulting in the dynamics of the bare airplane, with the added detrimental effects of the rate limiter itself.

Effects of Rate Limiting on Aircraft Response

In the absence of feedbacks, there is no difference between the command path and software rate limiters (Figure 1), and little difference between these and the rate-limited surface

actuator. Rate limiting with no feedbacks (or with the limiter outside the feedback paths) has a rather simple effect on the aircraft: the amplitude of response to control inputs is attenuated and phase is decreased.¹⁰ As an example, the frequency responses in Figure 2a are for pitch-attitude-to-stick-force frequency sweeps of an airplane with rate limiting upstream of the feedback path. Reduction in rate limits from 60 deg/sec to 20 deg/sec produces the expected results, with a consistent drop in output/input coherence.

The more complex problem arises when feedback loops are wrapped around the rate limiter, such as the software limiter in Figure 1. In this case, nibbling at the limiter produces an airplane that looks like a combination of the augmented and unaugmented vehicles, plus the characteristics of the limiting itself. In this case the impact of the limiter will depend upon how highly the airplane is augmented – that is, the difference in dynamics between the unaugmented and augmented vehicles – and how low the rate limit is set.

The example frequency responses in Figure 2b are for an airplane that is unstable with a time to double amplitude of roughly 0.5 sec, augmented to have a short-period mode with a damping ratio of 0.7 and natural frequency of 4.9 rad/sec. The result is an airplane that performs well for tight tracking tasks until the rate limiter is reached – then it is almost impossible to control. At a rate limit of 60 deg/sec, a relatively smooth frequency response results that closely resembles that of the 60-deg/sec configuration in Figure 2a. When the limit is 20 deg/sec (triangles in Figure 2b), the frequency response shows the basic loss of amplitude and phase that result from rate limiting, but the coherence becomes ragged and very low over a wide frequency range – the range over which the rate limiter is encountered.

Effects of Rate Limiting on PIO

While there is no question that rate limiting and PIO are related, the details of their relationship have not been fully defined. For example, it has not been determined if rate limiting, alone, can *cause* PIO, or is merely a *result* of PIO. The relationship between rate limiting and PIO has been investigated in several recent research studies, including a US Air Force Test Pilot School flight experiment³ on a variable-stability airplane, and numerous related ground-based simulations.⁷ Examination of selected configurations from these experiments illustrates the possible relationships between rate limiting and PIO. Four configurations, identified in the experiments as 2D, 2P, 2DU, and 2DV, will be discussed in this paper. Transfer functions of pitch rate to elevator deflection (short-period approximation) for the configurations are listed in Table 1.

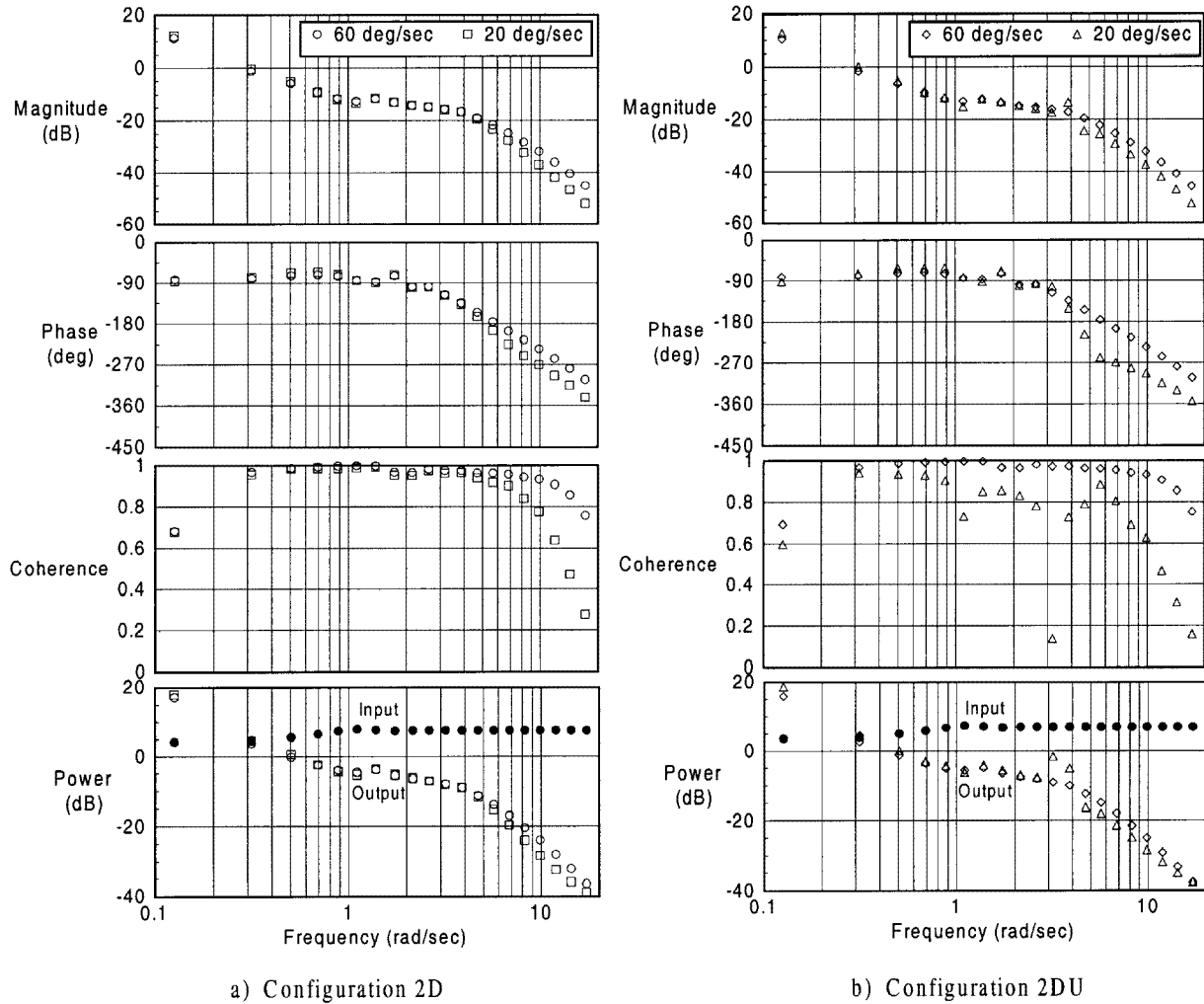


Figure 2. Effect of Rate Limiting Upstream (Part a) and Downstream (Part b) of Feedbacks on Pitch-Attitude-to-Stick-Force Frequency Responses

Table 1. Selected Configurations from HAVE LIMITS³ and PIO Simulation⁷

Config.	Fully augmented	Unaugmented
2D	$\frac{10(s+1.25)}{[s^2 + (0.7)(4.6)s + 4.6^2]}$	$\frac{10(s+1.25)}{[s^2 + (0.7)(4.6)s + 4.6^2]}$
2P	2D with added lag at $4/(s+4)$	
2DU	$\frac{10(s+1.25)}{[s^2 + (0.7)(4.6)s + 4.6^2]}$	$\frac{10(s+1.25)}{(s-1.33)(s+2.18)}$
2DV*	$\frac{10(s+1.25)}{[s^2 + (0.7)(4.6)s + 4.6^2]}$	$\frac{10(s+1.25)}{(s-0.52)(s+7.19)}$

*Evaluated in simulation only

The first set of values listed in Table 1 is for the non-rate-limited, fully-augmented case; the second set is with the augmentation loops opened, such as would occur with full rate saturation.

Configuration 2D (Table 1 and Figure 2a) did not exhibit PIOs for a HUD attitude tracking task with rate limits as low

as 10 deg/sec. For this configuration the function of the limiter was that of a command path limit (Figure 1), making no changes to the dynamics of the effective aircraft (compare columns for “fully augmented” and “unaugmented” dynamics in Table 1).

Frequency-response characteristics for Configuration 2D, obtained from analytical frequency sweeps of a mathematical model of the airplane, show a reduction in pitch attitude Bandwidth and increase in Phase Delay as rate limits are reduced (Figure 3). For sweep amplitudes that produce load factor changes of $\pm 2g$ or less, PIO is not predicted by criteria based on Bandwidth.⁵

A second configuration in the TPS experiment, Configuration 2DU (Table 1 and Figure 2b), exhibited rapidly divergent PIOs for rate limits as high as 60 deg/sec (the highest values evaluated were 60 and 157 deg/sec). In this case, augmentation was required to stabilize the airplane, and the slightest rate saturation resulted in almost immediate loss of control. As the analytically-derived frequency-response parameters show (Figure 4), rate limiting causes a sudden and dramatic increase in Phase Delay and loss of Bandwidth that corresponds to severe PIO.⁵

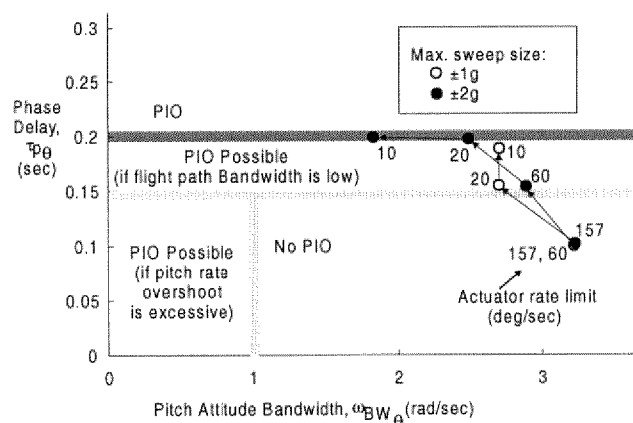


Figure 3. Effect of Rate Limit and Sweep Size on PIO Parameters for PIO-Resistant Airplane (Configuration 2D)

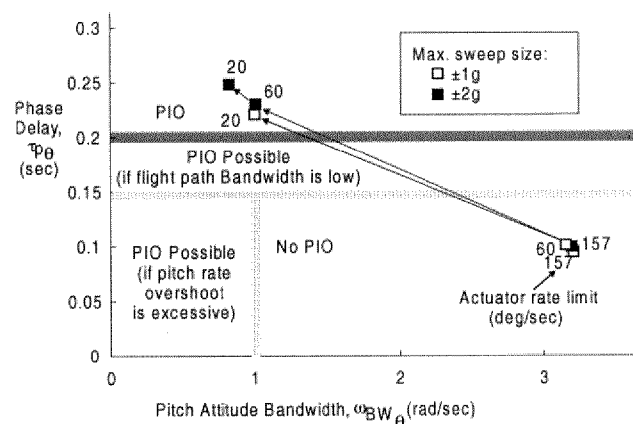


Figure 4. Effect of Rate Limit and Sweep Size on PIO Parameters for Highly PIO-Susceptible Airplane (Configuration 2DU)

The results of the HAVE LIMITS flight research project suggest that airplanes with sufficient Bandwidth are resistant to PIO. It is clear from the data generated in a moving-base simulation⁷ that rate limiting, alone, is not the culprit in Category II PIOs. By its nature, the nonlinearity is highly sensitive to several factors, including pilot input bandwidth, the amount of rate limiting experienced, and the consequences of reaching the rate limit.

As a graphical example, consider the data plotted in Figure 5. Percent of time on the rate limit was computed for several selected configurations, all flown by one of the most aggressive pilots in the simulation (Pilot C), and the numbers are plotted against Pilot C's assigned PIO Tendency Classification Rating (usually abbreviated PIOR for "PIO Rating") for that configuration/rate limit combination. Cooper-Harper Handling Qualities Ratings (HQRs) are noted next to each data point.

Lines connect individual data points in Figure 5 and progress from higher to lower actuator rates in all cases. For example, the circles are Configuration 2D with rate limits of 20 deg/sec (PIOR = 1) and 10 deg/sec (PIOR = 3). At the lower limit, the actuator was rate-saturated for 25% of the run. Still, Pilot C did not consider this airplane to have tendencies to PIO, nor did any of the other pilots who evaluated it, consistent with the HAVE LIMITS flight results for this configuration.

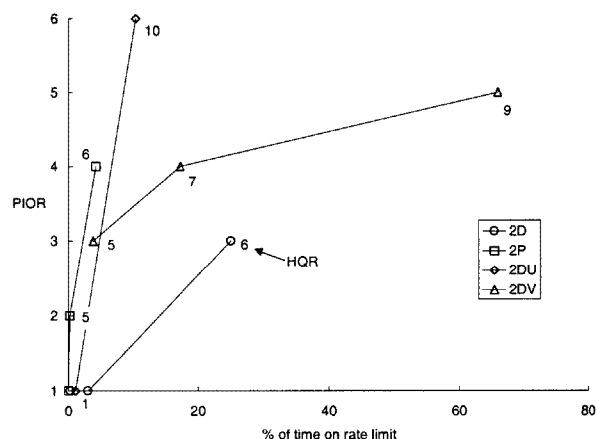


Figure 5. PIO Tendency Classification Rating (PIOR) as a Function of Percent of Time on Rate Limit for Selected Configurations (Data for Pilot C)

By contrast, for the sluggish Configuration 2P (2D with an added first-order lag filter at 4 rad/sec, squares on Figure 5), reductions in rate limit from 160 (PIOR = 1) to 10 deg/sec (PIOR = 4) resulted in an apparent tendency for PIO, even though the percent of time on the rate limiter increased to only 4% at the worst case. With augmentation and no rate saturation, Configuration 2DU (diamond symbols on Figure 5) flew like 2D and received a PIOR of 1. A reduction in rate limit to 30 deg/sec led to an occasional "nibble," resulting in saturation for only 1% of the run and no degradation in ratings. When the rate was decreased to 20 deg/sec, the overall percentage of time in saturation was only 10%, but it occurred all at once and resulted in a divergent PIO and a stoppage of the simulation. The PIOR of 6 and HQR of 10 reflect the extreme susceptibility to PIO for this configuration.

Because the bare-airframe dynamics for 2DV were not quite as unstable as those for 2DU, the trends are more gradual (triangles in Figure 5). With no saturation (fully augmented), 2DV looked like 2D (compare transfer functions in Table 1). The point with PIOR = 3 was for a 20-deg/sec rate limit, and it resulted in saturation for only 4% of the run, but that was enough to degrade the handling qualities. At a rate limit of 15 deg/sec, Pilot C was able to complete the task without crashing, with saturation 17% of the time and an assigned PIOR of 4. At the lowest rate limit of 10 deg/sec, Pilot C completed one run only with intense concentration, knowing that he was flying a highly PIO-susceptible configuration. He managed to maintain control of the airplane despite rate saturation for 66% of the run. His PIOR of 5 and HQR of 9 indicate the extremely poor characteristics of this configuration.

The data shown in Figure 5 simply serve to reinforce the observations that 1) hitting a rate limit, alone, and 2) spending considerable time on the rate limit, are not necessarily causes of PIO. The consequences of reaching the rate limiting, and the dynamics of the augmented airplane, are the key elements.

Rate Limiting and Pilot Technique

By their nature, the response dynamics of nonlinearities are dependent upon characteristics of the forcing function input – magnitude and form (frequency content). As a consequence, differences in piloting technique that may never show up in a linear system can become apparent in the presence of a nonlinearity.

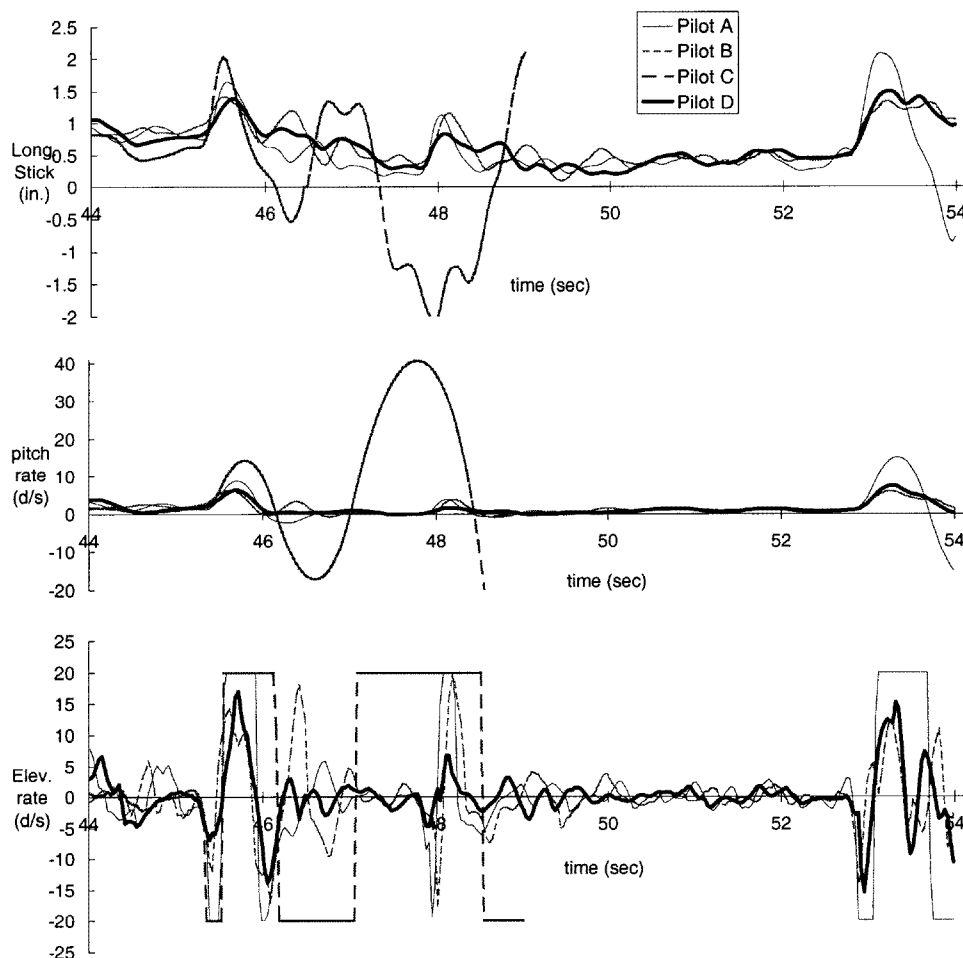


Figure 6. Sample Time History Comparison for Four Pilots Flying Configuration 2DU (20-deg/sec Rate Limit) in Moving-Base Simulation (HUD Tracking Task)

Strong evidence of this piloting difference was obtained in the recent moving-base simulation for Configuration 2DU with a 20-deg/sec rate limit (Figure 2b). Of the seven pilots who evaluated it, six experienced divergent PIOs with this configuration and assigned PIORs of 5 or 6, and HQRs of 10. The seventh pilot, however, did not experience the PIOs, and assigned a PIOR of 1 and HQR of 2. The piloting technique of this one pilot was clearly different and received a considerable amount of attention.

A 10-sec segment of selected time traces for Configuration 2DU with a 20-deg/sec rate limit is shown in Figure 6. Traces are longitudinal stick deflection, pitch rate, and elevator rate. The data for four pilots are shown: Pilots A and C (two of the most aggressive) and B and D (two of the least aggressive).

In the time history segment in Figure 6, Pilot C encounters divergent PIO following the pull at about 45 sec; his run was stopped at 49 sec due to the rapidly diverging response. Pilot A has just reached the same condition at the end of the segment, and his evaluation is stopped at about 56 sec. Pilot B managed to almost complete the run, with his run ending at 129 sec, while Pilot D completed the task without encountering divergent PIO.

There are some noticeable differences in Figure 6. For example, on the pull at approximately 45 sec Pilot C applies the largest input, generating the highest pitch rate, and leading to rate saturation of the elevator. Pilot A is second in input

size, resulting in a momentary saturation of the elevator, but he is able to recover by about 46 sec. Pilot B is third in aggressiveness, and his inputs at around 45 sec do not quite command the full 20 deg/sec of elevator rate. On several occasions during this segment Pilot B almost reaches rate saturation. Well below the other pilots is Pilot D, whose input magnitudes are almost always lowest, and his use of elevator rate is the lowest of all the pilots.

The time for peak input follows the same progression, with Pilot C generally applying the most rapid and D the least rapid (the pull at about 45 sec is the best example). These differences continue to show along the sequence for Pilots A, B, and D, even after Pilot C's run has ended.

COMMAND GEARING

Command gearing, or command/response sensitivity, describes the ratio of aircraft response (angular pitch acceleration or load factor) per unit command input (control deflection in inches or force in pounds). In flying-qualities research, we usually assume that the gearing is close to optimum for a particular airplane, either through pilot selection or *a priori* knowledge of pilot preferences. In addition, it is assumed that this gearing is constant with input amplitude. Both assumptions are generally incorrect in the real world, and gearing can have a direct impact on the occurrence of PIO.

Effects of Command Gearing on Aircraft Response

If the gearing is linear with amplitude, the only effect that changes in gearing will have on aircraft response is a shift in magnitude on frequency response plots. Nonlinear gearing can have a small effect on the overall quality of frequency response obtained from a pilot-generated frequency sweep.⁵

Three possible command shaping curves are sketched in Figure 7. (Only positive commands are represented in the figure; for this analysis, the commands were assumed to be symmetric.)

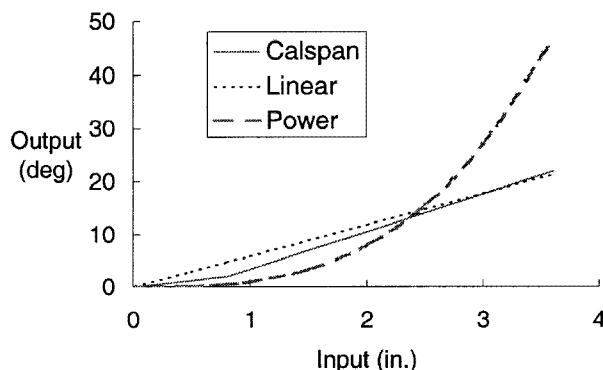


Figure 7. Command Shaping

The curve in Figure 7 labeled "Calspan" is the shaping used on the HAVE LIMITS flight experiment⁴ and includes a 0.02-in. deadband around zero. The linear command was selected to give approximately the same overall response for full control input (3.6 in. of stick deflection). The power curve is simply a cubic gradient of the form $y = x^3$ and is meant to represent an extreme form of nonlinearity. The power gradient would probably not be acceptable in flight, since it has very low control command at low deflections, and extremely high command at higher deflections.

There was no mechanical breakout force on the control stick in HAVE LIMITS, and breakout was not included in this analysis.

The effect of command shaping was investigated analytically using the dynamics of Configuration 2DU with a 20 deg/sec rate limit, and input sizes selected to achieve peak load factors of $\pm 1g$ from trim. As the response in Figure 2b (triangle symbols) shows, this configuration exhibits low coherence around 3 rad/sec, and again above about 10 rad/sec. Any additional complication from the change in input shaping should be apparent.

Frequency responses of pitch attitude to stick force for the three command gradients of Figure 7 are shown in Figure 8. The response labeled "Calspan" is identical to that in Figure 2b.

Changing the command shaping to purely linear (inverted open triangles in Figure 8) results in slightly higher magnitude overall. This translates to a slightly greater loss of phase at high frequencies, since the increased magnitude meant reaching the rate limiter at a slightly lower frequency. There is a slight improvement in coherence at almost all frequencies, especially above 10 rad/sec, possibly because of the more linear nature of the command in combination with the nonlinearity of the rate limiting. In general, however, the frequency response is not significantly changed from the Calspan shaping case.

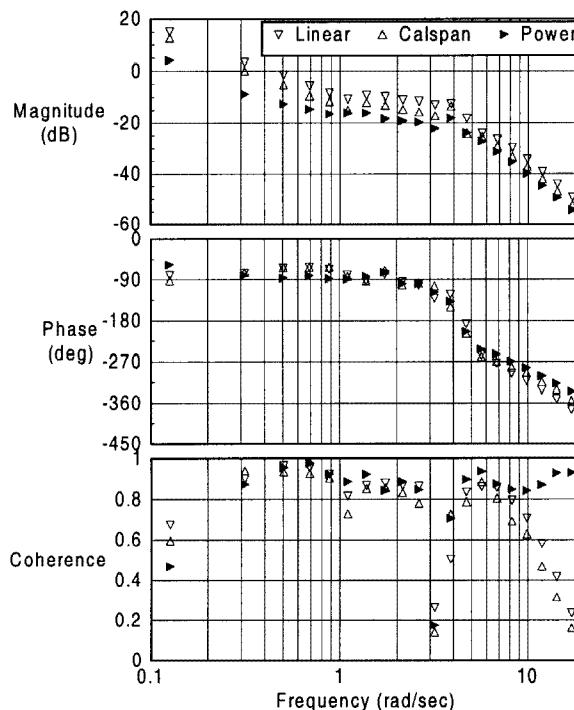


Figure 8. Effect of Command Shaping on Frequency Response (Configuration 2DU, 20 deg/sec Rate Limit, $\pm 1g$ Load Factor Change)

Trends for the power curve are almost the opposite of those for linear in Figure 8: magnitude is slightly lower and phase loss is slightly less. As with the linear case, coherence is generally better at all frequencies, but in the ballpark of both other cases.

Effects of Command Gearing on PIO

In most research projects, command gearing has been either pilot-selectable or set by the experimenters at the outset. In either case it is possible that the inappropriate gearing has been selected.

Pitch Command Gearing

We have only a little evidence of the effect of pitch command sensitivity on PIO. A small example can be obtained from a 1986 flight research experiment on the Air Force's Total In-Flight Simulator, TIFS. In that study,¹² the majority of the pitch configurations had a "nominal" value of pitch command sensitivity, $\dot{q}/F_s = 0.42$ deg/sec²/lb. A portion of the study investigated the effects of changes in sensitivity, repeating some configurations with a "high" value of 0.63 deg/sec²/lb and others with a "low" value of 0.25 deg/sec²/lb. The three sets of sensitivity were applied to two good configurations, to which time delay values of 0.1 and 0.2 sec were added.

Results for this experiment are shown in Figure 9. The plot shows added time delay versus pitch command sensitivity, with PIORs noted next to each data point. HQRs are in brackets below the PIORs. Slashes separate ratings from different pilots and commas separate repeats by the same pilot. The trends show that, with no added time delay, any value of sensitivity is acceptable as far as PIO tendency. There are Level 2 HQRs (4 and 5) for the high and low sensitivity values, suggesting the nominal value of 0.42 is best.

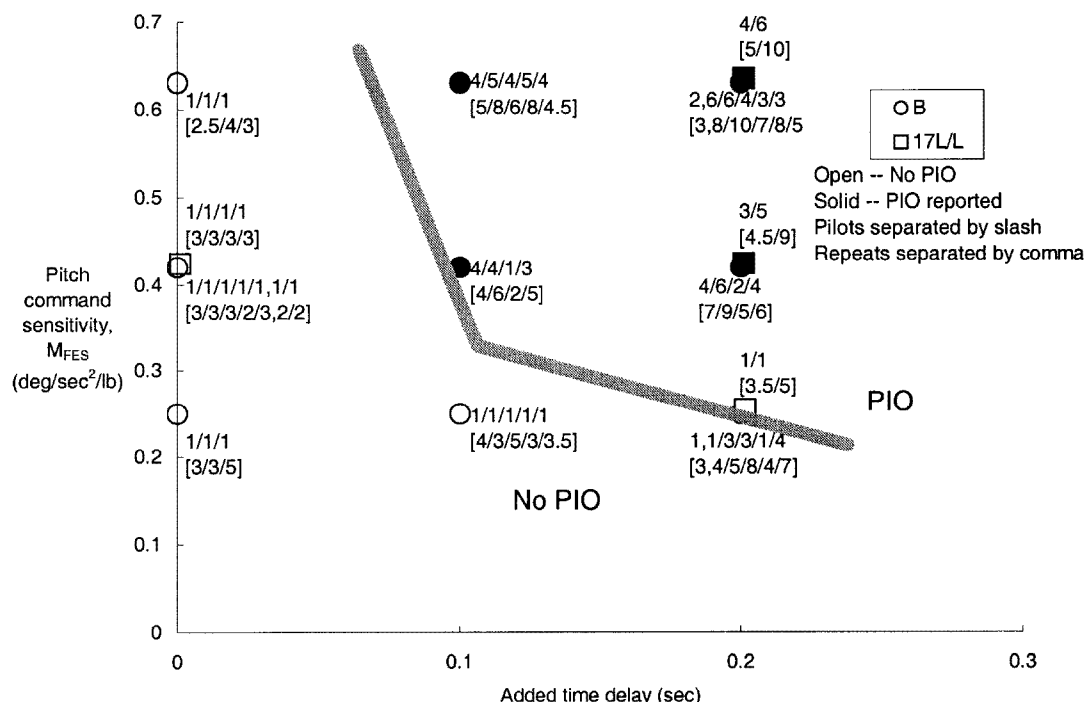


Figure 9. Effect of Pitch Command Sensitivity on PIO as a Function of Added Time Delay (Ratings are PIORs with HQRs in Brackets)

As time delay is added, however, the data in Figure 9 suggest a preference for lower values of pitch command sensitivity. When 0.1 sec of delay is added, there are reports of “moderate” PIO (HQRs better than 7) for the nominal sensitivity; with the high value, severe PIOs are reported; but for the low value, not only is there no indication of PIO, but the PIORs from five different pilots are all 1’s, suggesting there was not even a hint of undesirable motions, either.

With 0.2 sec of added delay, only one pilot out of seven (counting both configurations) considered the low-sensitivity cases to exhibit PIO, while the nominal and high cases exhibited severe PIOs.

These data clearly suggest that 1) the “nominal” value of pitch sensitivity, $\dot{q}/F_s = 0.42$ deg/sec²/lb, used in the study¹² was too high when time delay was added, and 2) it is possible to minimize the risk of PIO by adjusting pitch sensitivity to suit the dynamics of the airplane.

Support for the first observation can be gleaned from the pilot comments for the experiment; several pilots complained of excessive sensitivity and very light control forces, many of these associated with PIOs. These observations have also been confirmed by a series of flight experiments conducted by Boeing, Long Beach, in cooperation with the Air Force.¹³

The Boeing experiments, also performed on the TIFS, included two baseline Level 1 configurations to which were added time delays of 0.125 and 0.275 sec. Each of these configurations was evaluated at two pitch command sensitivities, a nominal value of 0.3 deg/sec²/lb, and an increased value of 0.45 deg/sec²/lb. These values approximately correlate with the “low” and “nominal” values of the Calspan experiment.¹² For the zero added time delay configurations the increased pitch command sensitivity did not cause PIO. For the configurations with added time delay, however, the increased pitch command sensitivity resulted in increased PIO tendencies.

Roll Command Gearing

Roll sensitivity is the initial acceleration per pound, written as either the lateral sensitivity derivative L_{FAS} , or simply as \dot{p}/F_{AS} , both in units of deg/sec²/lb. Results of two roll experiments^{14,15} show trends similar to those for pitch. In both experiments the simulated airplane was a fighter performing air combat tracking tasks.

Figure 10 shows a plot of roll command sensitivity versus added time delay for a configuration from the LATHOS program¹⁴ with roll damping $T_R = 0.3$ sec. Unfortunately, because PIO tendency ratings were not gathered in this experiment, we must rely on pilot comments and Handling Qualities Ratings to determine where PIO occurred. The ratings in Figure 10 are for the three pilots, separated by slashes; commas separate repeat evaluations by the same pilot. In several cases, at least one of the pilots reported a tendency for roll ratchet, rather than PIO, and this is noted by an “R” beside that symbol.

The data in Figure 10 clearly show a trend for reduced PIO tendency as roll sensitivity is reduced. Generally, pilot ratings degrade to Level 3 at about the same value of added time delay for all three values of sensitivity.

The importance of the linearity – or more correctly, the nonlinearity – of command shaping on flying qualities was demonstrated in the LATHOS flight research program¹⁴ conducted by Calspan on the NT-33A. For roll maneuvering, configurations with high roll damping and essentially linear command shaping were susceptible to high-frequency roll oscillations identified as “roll ratchet”; addition of only a slight amount of shaping, around zero control input, improved the flying qualities drastically.¹⁶ (Unfortunately, no explicit information on PIO was obtained for the experiment, so we cannot directly judge the impact of the changes in command shaping on PIO alone.)

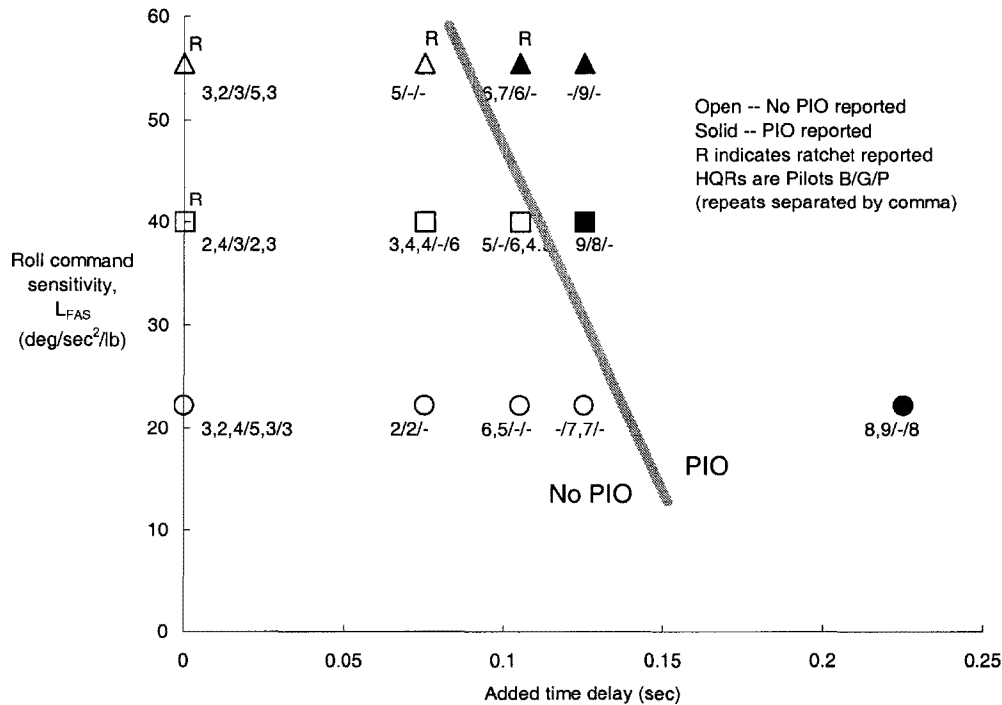


Figure 10. Effects of Roll Command Sensitivity on PIO Tendency as a Function of Added Time Delay (Configuration with Roll Damping $T_R = 0.3$ sec)

BREAKOUT AND HYSTERESIS

Breakout and hysteresis (freeplay) are unavoidable characteristics of mechanical control systems, and some degree of both is desirable. There is little in the way of quantitative information on the effects of such elements on PIO, so we can only discuss the issues involved.

Effects of Breakout on Aircraft Response

Breakout exhibits gain attenuation but has no effect on phase, so it can be represented by a simple describing function.⁹ Its impact on aircraft response will be minimal, though measurements of effective control sensitivity or control power will be affected by the presence of a breakout.

Effects of Breakout on PIO

A small deadzone in a mechanical cockpit controller effectively desensitizes the controller for very small inputs. Too little breakout may make the airplane prone to high-frequency phenomena such as roll ratchet. Excessive breakout reduces precision, and may contribute to PIO by driving the pilot into overcontrol.

Effects of Hysteresis on Aircraft Response

Hysteresis introduces an attenuation in amplitude and loss of phase at all frequencies, the magnitude of which is dependent upon the ratio of depth of the hysteresis and input amplitude (Figure 11). The characteristics of hysteresis are described by the magnitudes of the nonlinearity 'a' and the input signal 'A'. The magnitude of the output is limited to 'A-a', and the output is lagged behind the input. The magnitude limiting causes the gain attenuation and the lag provides the phase loss.

The sinusoidal describing function for hysteresis is shown graphically in Figure 12. The magnitude of the gain attenuation and phase loss provided by the hysteresis is simply a function of the ratio of the magnitudes of the nonlinearity to the input, 'a/A' (see the sketches in Figure 11). When 'a/A' is zero (zero deadband), there is no gain attenuation or phase loss. As 'a/A' increases both gain and phase loss increase as the effect of part of the applied force is now lost in the deadband zone (-a to +a). As 'a/A' increases towards 1 (all applied force is in the deadband region) the gain attenuation approaches infinity: there is no output to the corresponding input.

Since hysteresis in the control system is a frequency independent nonlinearity, it will cause uniform gain and phase attenuation at all frequencies, as sketched in the aircraft frequency responses of Figure 13. Any parameters measured from the frequency responses will reflect the reduction in overall amplitude and bandwidth introduced by hysteresis.

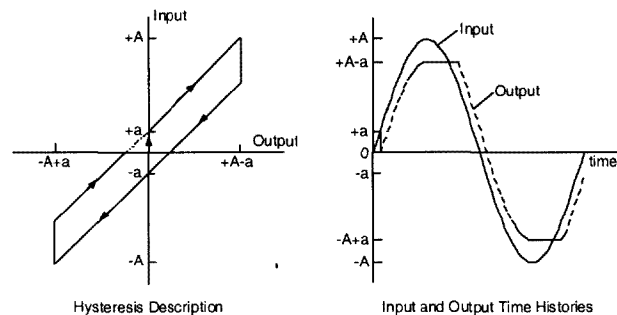


Figure 11. Hysteresis and Its Effect on Time Response

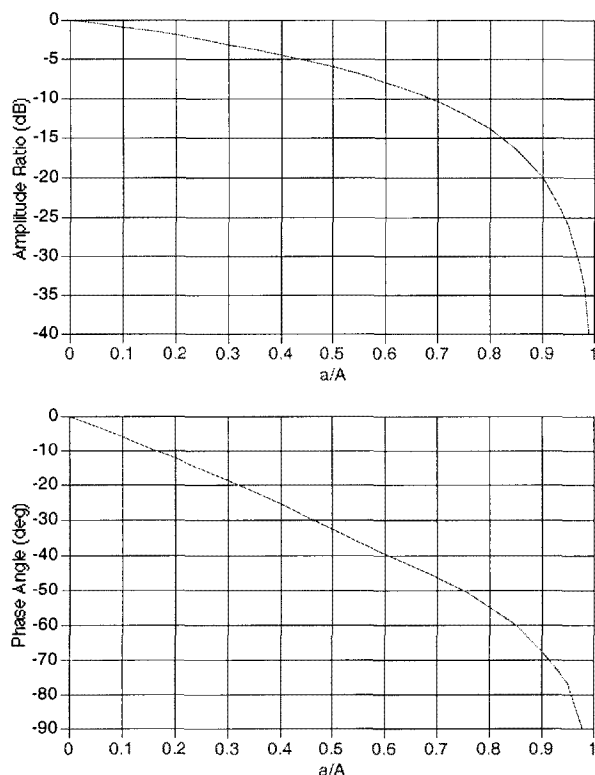


Figure 12. Sinusoidal Describing Function for Hysteresis⁹

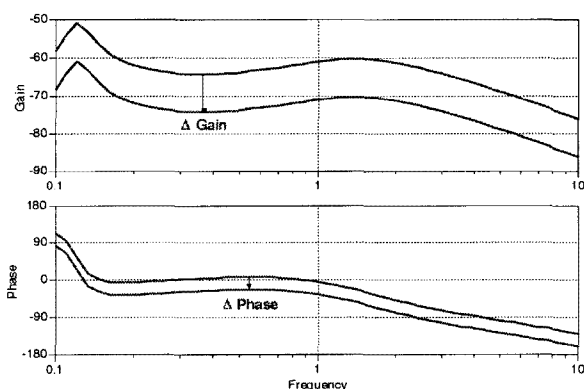


Figure 13. Effects of Hysteresis on Analytically Derived Frequency Response

Effects of Hysteresis on PIO

The phase loss and gain attenuation introduced to the frequency responses by the nonlinearities in the control system will have implications for flying qualities and PIO susceptibility of the aircraft. Linear analyses that exclude these nonlinearities are prone to error, and are likely to predict better flying qualities and lower PIO susceptibility than the real aircraft will exhibit. The choice of whether to use stick force or stick position as the input for such analyses will affect the results, since the feel system includes nonlinear effects such as hysteresis.

There is little information on the impact of hysteresis on PIO. As with breakout, it can be hypothesized that an excessive level of hysteresis will adversely impact flying qualities and increase the potential for PIO.

CRITERIA FOR THE REDUCTION OF PIO SUSCEPTIBILITY

PIO will never be eliminated from advanced aircraft. As long as there is a continuing push to reduce aerodynamic surface size, and increase the role of artificial augmentation, the potential for PIO will exist. Recent work has led to several proposed criteria for the reduction of PIO susceptibility. Based on a comparative assessment for Category I PIOs, criteria based on airplane Bandwidth were most effective at predicting the possibility for PIO.¹⁷

Parameters

Parameters for the airplane Bandwidth criteria are defined in Figure 14 and Figure 15.

For a purely linear airplane, a frequency response such as that in Figure 14 represents the dynamics of the augmented airplane for all input amplitudes. More typically, in the presence of nonlinearities the frequency response will be more like those shown in Figure 2: regions of low coherence and possibly non-trustworthy data, with large changes in both magnitude and phase angle of the frequency response.

Criteria

Limits for PIO and handling qualities Levels, for pitch response when the feel system is excluded from the dynamics of the aircraft, are shown in Figure 16. Experiences with these criteria – including the results shown in both Figure 3 and Figure 4 – strongly support their use as PIO prediction and prevention criteria.

The boundaries in Figure 16 are slightly different from those in Figure 3 and Figure 4: the latter include the dynamics of the cockpit force feel system, and hence the limits on the Phase Delay parameter are slightly higher.

Steps for Obtaining the Bandwidth Parameters in the Presence of Nonlinearities

Because it is difficult to obtain flight data for large control inputs, analytical models, in careful consonance with existing flight data, must be used to generate the frequency responses needed to test for PIO susceptibility. Some recommended steps for obtaining the required frequency-response data and parameters are given in Table 2.

With only slight modifications to the steps in Table 2, primarily in modifying the techniques and frequency ranges for the control-input frequency sweeps, the data generated can be used very effectively for parameter identification as well. The steps outlined in Table 2 are specifically oriented toward the Bandwidth criteria and their parameters and focus on the frequency ranges needed for the criteria.

CONCLUSIONS

Advanced flight control systems introduce the potential for significant nonlinearities in aircraft response. The occurrence of pilot-induced oscillations has been attributed to several of these nonlinearities.

This paper examined the results of recent simulation and flight research into the influence of actuator rate limiting (including limiting of software elements intended to prevent reaching the limits of the actuators) on PIO.

- The research data – as well as practical experience – indicate that rate limiting, alone, does not necessarily cause PIO.

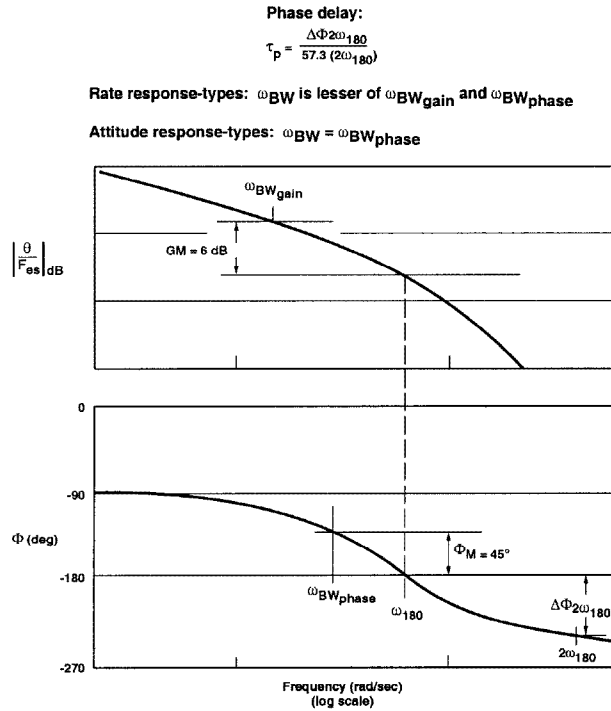


Figure 14. Pitch Attitude Bandwidth and Phase Delay
 (Flight Path Bandwidth ω_{BW_γ} is Measured from γ/F_{es} and
 is Defined as $\omega_{BW_{phase}}$)

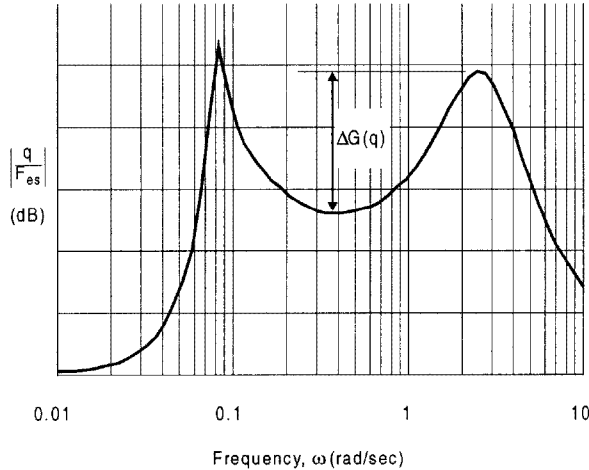


Figure 15. Definition of Pitch Rate Overshoot Parameter, $\Delta G(q)$

- If an airplane has sufficient stability, the deleterious effects of rate limiting will not directly lead to PIO.
- There are three principal factors that determine the susceptibility to PIO for an augmented airplane: the location of the limiter, the degree of stability (or instability) of the airplane, and the demands made on the airplane.
- Rate limiting in the feedforward path (with feedback loops wrapped around it) is the most critical element of PIO susceptibility, since saturation will effectively open the feedback loops and introduce the gain attenuation and phase loss inherent to such limiting.

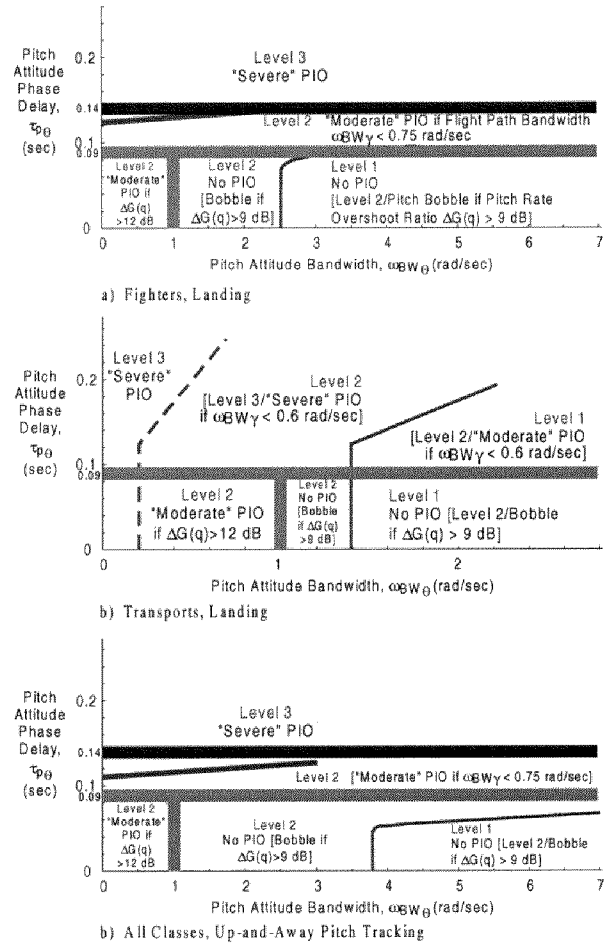


Figure 16. PIO Criteria for Pitch Response When the Dynamics of the Cockpit Control Feel System are Excluded

- Saturation of a limiter in the feedforward path is especially devastating if the augmentation is needed to stabilize a highly unstable airplane. With saturation, the change in dynamics may be more than the pilot can compensate for, again when the limiting itself further degrades the dynamics of the airplane.
- In combination with location of the limiter and the consequences of saturation, the demands placed on the flight control system are a factor. If only occasional "nibbling" at a rate limiter occurs on an airplane that is highly augmented but only slightly unstable, PIO is not likely to develop. But larger demands on that airplane lead to a further separation between demanded and achieved, and greatly increase the likelihood for PIO.

Overall, for aircraft that take full advantage of advanced flight control systems, the key to avoiding PIO is to avoid rate limiting. Since this is not always possible, it is less hazardous to encounter software limiting ahead of all feedback loops than within any such loops.

While not a true source of nonlinearity, the command sensitivity (commanded acceleration per unit cockpit control deflection or force) can have an effect on the susceptibility to PIO as well. Research suggests that as overall time delay increases, a reduction in command sensitivity can reduce the potential for PIO.

Table 2. Recommended Steps for Determining Bandwidth Parameters from Flight Test

<i>Required Data: pitch rate (\dot{q}), vertical velocity (\dot{h}), and cockpit control force (F_{es}) or position (δ_{es})</i>	Define dynamics of prefilters and sensors for all signals
	Use instantaneous data (such as IVSI) as opposed to lagged data
	Verify correct sequence for data sampling and recording: all data from same time frame
<i>Frequency Sweeps (General)</i>	Frequency range can be narrow <ul style="list-style-type: none"> – Lowest frequency around 0.2 rad/sec or 0.03 Hz (30 seconds per cycle) – Highest frequency around 12-18 rad/sec or 2-3 Hz (3 cycles per second)
	Start from and end in trim conditions, sweeping from lowest to highest frequency
	Total time for the sweep should be no less than about 90 seconds
	Attempt to keep input amplitude relatively constant (smaller amplitude will be necessary for very low-frequency portion of sweep)
	Pilot-generated sweeps are preferred; pilot should be allowed to assist automated sweeps to remain near trim conditions
	Avoid dwelling at frequencies of aircraft natural response (linear and nonlinear modes)
	Repeat sweeps are useful
<i>Frequency Sweeps in Simulation</i>	Confirm that model includes expected nonlinearities <ul style="list-style-type: none"> – Control command shaping and control feel dynamics – Actuator rate and position limits – Surface effectiveness variations
	Run sweeps of varying input amplitude <ul style="list-style-type: none"> – Linear region of aerodynamics/control system: peak pitch rates of ± 10 deg/sec – Near normal acceleration limits: between 0 and 2g for transports, larger for fighters – At or near full stick (will probably require automated inputs at higher frequencies)
<i>Frequency Sweeps in Flight</i>	Run sweeps of varying input amplitude <ul style="list-style-type: none"> – Linear region of aerodynamics/control system: peak pitch rates of ± 10 deg/sec – Normal acceleration range of 0-2g (if peak pitch rates ± 10 deg/sec do not cover this load factor range)
	Confirm that flight results are consistent with those from simulation
	Adjust simulation as necessary to improve correlation
<i>Determination of PIO Susceptibility</i>	Check both simulator and flight results with requirements <ul style="list-style-type: none"> – Generate required frequency responses using reliable software (e.g., CIPHER) – If a “dip” occurs in coherence at any frequency where both input and output powers are high, use single sinewaves at the amplitude of the corresponding sweep and around the frequencies of the loss of coherence to verify results of the sweep – Convert pitch-rate-to-control-force response to effective pitch attitude (add 1/s) – Measure Bandwidth parameters
	Confirm that simulator and flight results are in good agreement for small-amplitude sweeps <ul style="list-style-type: none"> – If no PIO is predicted, no further testing is needed – If PIO is predicted from both simulation and flight, piloted closed-loop tracking should be performed in flight to test for susceptibility – If PIO is predicted from simulation for large-amplitude sweeps, further flight testing is necessary to confirm this
	Sensitivity to increases in input amplitude may be spot-checked in flight <ul style="list-style-type: none"> – Note frequency where pitch attitude is 180 degrees out of phase with stick, $\omega_{180\phi}$ (equivalently, where pitch rate is 90 degrees out of phase with stick, $\omega_{90\dot{q}}$) – Apply several cycles of a sinewave at this frequency in flight, at highest control amplitude used for in-flight frequency sweeps – Repeat for progressively higher control input amplitudes, as flight safety allows – Analyze the single frequencies using time-series analysis (measure amplitude ratio and phase angle directly from time responses) – Compare the loss in phase with the full frequency sweep at the single frequency – This will provide a rough measure of the amplitude attenuation and phase rolloff with increasing amplitude without performing a full frequency sweep

Finally, characteristics of the mechanical cockpit controller, such as breakout and hysteresis, introduce gain attenuation and phase lag into the frequency response that may lead to an increased susceptibility to PIO.

Criteria for the reduction of PIO risk, and steps for obtaining the required frequency-response data and Bandwidth parameters, have been developed and were documented in this paper.

ACKNOWLEDGEMENTS

Most of the work presented here was supported by Contract No. F33615-95-C-3608 from the U.S. Air Force, Wright Laboratory, Wright-Patterson AFB, Ohio. Mr. Thomas J. Cord was the Air Force Contract Monitor. A portion of the work was performed through funding from The Boeing Company, Phantom Works, Long Beach, CA.

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Paper#A28

Q by David Moorhouse: Your paper illustrates the adverse effects of rate limits put in the wrong position in the control system. In that sense it is consistent with the best practices of paper #25. Would you please comment.

A. (Dave Mitchell & Edmund Field): That is true. More than that, however, we recognize that rate limiting is unavoidable, that any mechanical system can be driven to saturation. The question to be addressed is whether the aircraft flying qualities are affected. We tried to emphasize the importance of properly accounting for the adverse effects of rate limiting on handling qualities and PIO, and of avoiding rate limiting that is not compatible with the dynamics of the aircraft.

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